Site-Specific Sprinkler Irrigation in a Water-Limited Future

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Abstract. *Available water supplies for irrigation are becoming more and more limited in the western U.S. and other locations around the world, and this downward trend is accelerating. These issues will force major changes to physical and managerial aspects as well as the design of water delivery and on-farm irrigation systems. Thus, a water- and energy-limited future will be the likely catalyst that finally brings many of the existing precision agricultural technologies together for irrigated agriculture. Resource conservation as well as achieving environmental benefits will probably require the adoption of non-uniform water applications, also known as site-specific irrigation, for many growers. The goal of site-specific irrigation is to conserve water by directing the amount and frequency of water applications according to established spatial and temporal crop water requirements. However, more than 20 years of private and public research on site-specific irrigation has resulted in very limited commercial adoption of the technology. The current state of the art of site-specific center-pivot and linear-move sprinkler irrigation is reviewed. Several general barriers to adoption of the technology and various knowledge gaps are identified. The primary reason for the very low rate of commercial adoption appears to be the absence of a market for the technology and a low rate of return. Documented and proven water conservation strategies using site-specific sprinkler irrigation for crop production are quite limited, and its cost-effectiveness has not been demonstrated. Simulation studies comparing conventional and site-specific irrigation have reported water savings of 0% to 26% for well-watered crop production, and the greatest savings are most likely to occur in humid climates by spatially maximizing utilization of non-uniform growing season precipitation. In arid and semi-arid climates, the greatest potential water savings could come from highly managed deficit irrigation strategies in which spatial management of soil water deficit timing is used to maximize net return rather than yield. Future research needs to focus on developing and documenting cost-effective site-specific water conservation strategies to support market development for these advanced and needed irrigation technologies.*

Keywords. *Adaptive control systems, Decision support, Irrigation controls, Precision agriculture, Precision irrigation, Sensor systems, Spatial variability, Water management.*

Major stresses will continue to be progressively imposed on existing water resources around the world due to increasing global population, negative water quality trends in aquatic and riparian ecosystems, endangered species regulations, increased demands from tourism and recreation, international and interstate agreements, and a rising world standard of living. At the same time, arable land degradation is increasing due to salinity, soil erosion, and desertification as well as the need for additional land for residential, industrial, and transportation land uses, which are collectively reducing the available land base for production agriculture. The Food and Agriculture Organization (FAO, 2010) estimated that about 925 million people in the world were malnourished in 2010, and an even greater number suffered from unsafe drinking water supplies and inadequate sanitation.

Global climate change may further exacerbate these problems through changing temperatures and long-term variations in annual precipitation amounts and regional rainfall distribution patterns. Hydrologic uncertainties are compounded because modifications in precipitation and temperature can have disproportionately large effects on crop evapotranspiration (ET) as well as the volume and timing of stream flows, especially in arid and semiarid areas. The combination of these factors will force changes in the distribution of where and which crops are grown and whether or not water is available for irrigation, and, if so, how much and what quality water will be available.

These significant issues are focusing increasing attention on improving irrigated agriculture's ability to produce needed food, fiber, biofuels, and livestock feed with reduced water supplies through conservation and the implementation of advanced technology (Postel, 1999;

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Clemmens and Allen, 2005; Stone et al., 2010). There is little doubt that irrigated agriculture faces a water- and energy-limited future, and these trends do not portend well for increased crop production using current strategies and management. Combining a fully exploited land base with the growing competition for existing freshwater supplies will require that irrigators substantially increase efficiency and productivity per unit of water consumed (Postel, 1999; Pereira et al., 2002; Spears, 2003; Khan et al., 2006; Evans and Sadler, 2008).

One technology that will potentially play a major role in future irrigation management of limited water supplies is site-specific variable-rate sprinkler irrigation (SS-VRI) with self-propelled center-pivot and linear-move systems. This article reviews the current state of the art of site-specific center-pivot and linear-move sprinkler irrigation, identifies several general barriers to adoption of the technology, and presents various knowledge gaps that need to be addressed.

SELF-PROPELLED SPRINKLER IRRIGATION

Approximately 56% of all irrigated lands in the U.S. utilize various sprinkler irrigation methods. During the five-year period from 2003 to 2008, the total area irrigated in the U.S. by all sprinklers increased almost 15% to 12.5 M ha (30.9 million ac) (USDA-NASS, 2009). Self-propelled center-pivot and linear-move sprinkler systems account for about 84% of all sprinkler irrigation systems and are being used on about 10.5 M ha (26 million acres) in the U.S. This is an increase of about 20% from 2003 (USDA-NASS, 2009.)

It is estimated that there are more than 175,000 center-pivot irrigation systems in the U.S., and the proportion of the U.S. irrigated land base covered by these machines is continuing to grow. Most of this growth has been with center-pivot rather than linear-move sprinkler systems, with much of the recent increases occurring in the southeast U.S. and lower Mississippi River Valley (USDA-NASS, 2009.)

Self-propelled center-pivot and linear-move sprinkler systems are generally used on large blocks of lower-value field crops and cover a much greater area due to lower per acre capital and maintenance costs than most micro-irrigation methods. In addition, self-propelled sprinkler systems can have more flexibility in adjusting management of spatially changing management zones than microirrigation systems. These sprinkler systems are well-suited for large fields, and most of the land area converting to improved irrigation technologies in the future will probably utilize self-propelled sprinkler systems.

VARIABILITY IN IRRIGATED FIELDS

One of the greatest constraints to managing for enhanced productivity as well as water quality is the inability of agricultural producers to control inputs in ways that accommodate variable growing conditions across a relatively large field (e.g., >10 ha). Infiltration rates have long been known to vary between irrigation events, but they also vary among locations within a field. In addition, for any given field, wide variations can occur because of topographic redistribution of runoff, soil chemical properties, soil water holding capacities, subsurface conditions, soil drainage, insect/weed/disease problems, soil compaction, and wind distortion of sprinkler patterns. Field variability may also be impacted by tillage practices as well as herbicide carryover effects in the soil (Han et al., 1996; Evans and Harting, 1999). Irrigation system design and management can also be sources of variability.

Actual crop evapotranspiration (ET) can vary in space and time even under conditions of relatively abundant water. These variations can be the result of many interacting factors, including: differences in crop genetics, plant density and weed competition that affect vegetative growth rates and cover, nutrient availability and timing, stage of growth, and vigor. Localized differences in incident precipitation and soil water availability, soil depth, slope, and soil salinity can greatly impact ET and thereby crop yield and quality. Variations in pest intensity and timing can also affect crop ET.

While site-specific agricultural technologies (precision agriculture) such as variable-rate fertilizer applications, seeding (e.g., changing varieties or densities with location within a single field), variable-rate pest management, and variable-rate irrigation systems have long been used separately, economic and social mandates to reduce input costs and conserve water will cause the convergence of several site-specific agriculture practices to become more fully integrated into farm management programs to reduce total inputs per unit area to maximize output per unit of water and reduce costs. For example, site-specific irrigation may also require site-specific adjustments in fertilizer applications.

SITE-SPECIFIC SPRINKLER IRRIGATION

One of the basic premises of site-specific precision agriculture (PA) technologies in general is that crop growth is non-uniform across a field for many reasons, and therefore the requirements for inputs of water and nutrients also vary. Site-specific irrigation is defined as spatially varying the irrigation applications in ways that optimize plant responses for each unit of water applied. Site-specific water application technologies make it possible to vary both water and some agrochemicals to meet the specific needs of a crop in each unique zone within a field.

Self-propelled center-pivot and linear-move sprinkler systems that apply water at differential rates as the machines move across the field to adjust for temporal and variability in soil and plant conditions are commonly referred to as site-specific variable-rate irrigation (SS-VRI). Ideally, weather stations, mobile sensors, and distributed in-field networks of soil, environmental, and/or thermal sensors with wireless communications are integrated into a real-time, automated decision support system to help guide this process. SS-VRI is generally included in the definition of a precision agriculture (PA) technology, and uses many of the same management tools.

PA technologies have the basic attributes of site-specific treatments to discrete portions of a field and the use of global postioning systems (GPS). They include site-specific aspects of planting, fertilizer applications, pest management, and irrigation designed to manage spatial and temporal variability within agricultural fields. Management tools include various types of sensing systems, field sampling, geographic information systems, GPS, wireless communications, on-the-go yield monitoring, and decision support systems. However, because of complex spatial and temporal interrelationships, implementation of SS-VRI generally has the most difficult requirements and the most complicated and costly control systems of all PA technologies. SS-VRI is also the most expensive in terms of management because of the complexity and much higher frequency of treatments compared to other PA technologies.

In this article, site-specific irrigation or site-specific variable-rate irrigation are the preferred terms rather than precision irrigation. The widely used term "precision irrigation" has many definitions that do not always include site-specific considerations. For example, precision irrigation is also used to describe various water application devices as well as the accuracy at which water is uniformly applied across an entire field with microirrigation irrigation systems.

Self-propelled center-pivot and linear-move irrigation systems are particularly amenable to site-specific approaches because of their current level of automation and large area coverage with a single lateral pipe. These technologies can be used to treat small areas of a field, as in single span-wide treatment areas, or to treat various parts of the whole field by controlling sprinkler heads in all spans. Reducing excess water applications also decreases the potential for runoff and the movement of nutrients and agrochemicals below the plant root zone (King et al., 1995; Sadler et al., 2000, 2005; King et al., 2009) while optimizing crop yield and quality. However, the research to support these objectives has not been done.

Several innovative technologies have been developed to variably apply irrigation water to meet anticipated whole-field management needs with site-specific irrigation, primarily with center-pivot and linear-move sprinkler irrigation systems. The basic requirements for site-specific applications with these machines include various methods to vary water application depths, a method of position determination (e.g., GPS), and a microprocessor-based device to control water application amounts from each sprinkler head or groups of sprinkler heads based on location and other management criteria. These systems may also require modifications to the water supply delivery system to handle variable-rate water demands as well as the capability for variable-rate nutrient injection and variable-rate pesticide application (Roth and Gardner, 1989; Sumner et al., 1997; Miranda et al., 2003; Palacin et al., 2005; Farahani et al., 2006; King et al., 2009).

Site-specific irrigation using self-propelled center-pivot and linear-move systems has been studied by researchers in several states, including Colorado (Fraisse et al., 1992; Duke et al., 1992), Idaho (King et al., 1995; McCann et al., 1997), Washington (Evans et al., 1996), South Carolina (Camp and Sadler, 1994; Omary et al., 1997; Camp et al., 2002), Georgia (Perry et al., 2003, 2004; Dukes and Perry, 2006; Han et al., 2009), and Montana (Kim et al., 2008, 2009; Evans et al., 2010). Several of the older studies were summarized in the proceedings of a 2000 ASAE conference (Buchleiter et al., 2000; Evans et al., 2000; Sadler et al., 2000). Kranz (2009) and Kranz et al. (2010) summarized the characteristics of some of the various commercial site-specific control systems.

Recent innovative work on site-specific sprinkler irrigation in Washington has also been reported by Pierce et al. (2006) and Chávez et al. (2010a, 2010b, 2010c). Other groups in Europe (Al-Kufaishi et al., 2006) and Brazil (R. D. Coelho, 2009, personal communication) are also investigating various aspects of site-specific irrigation with self-propelled sprinkler irrigation systems. Integrating soil moisture monitoring with center-pivot controls is beginning to receive commercial attention by center-pivot manufacturers.

The potential benefits of site-specific, variable-rate irrigation have been reported by Sadler et al. (2005), Andrade-Sánchez et al. (2007), Kim and Evans (2009), O' Shaughnessy and Evett (2010), and others. However, there is very little scientific information documenting the capability of site-specific sprinkler irrigation systems to conserve water or energy on a field scale for crop production in either arid or humid environments. In addition, the hydrologic conditions of reported studies were usually not widespread enough to be able to denote large-scale water savings. Most of the past research has been to maximize yields, and ascribed water savings were basically treating symptoms of overirrigation under conditions of adequate water, which is generally the case when there is little incentive to save other than slightly reduced energy costs.

Water Conservation with Site-Specific Irrigation

Reduced availability of water and energy for irrigated agriculture will require much greater levels of crop and water management than currently in use; this will be extremely difficult, if not impossible, without advanced irrigation methods. The potential to conserve water depends on the capabilities of the irrigation system and the commitment of the operator to implement timely water-saving practices and technologies (Schütze and Schmitz, 2009).

There are ways in which more water could be conserved with basic self-propelled center-pivot or linear-move sprinkler systems that do not require large management changes. For example, a simple water conservation alternative is to restrict or eliminate the use of end guns, which is probably the area with most inefficient use of water under the entire machine (Solomon and Kodoma, 1978). However, this is currently unacceptable to most producers because it would also reduce total yields from a field as less area is irrigated. Conversion to low-energy precision application (LEPA) nozzles would also effectively reduce evaporation losses and substantially increase application efficiencies (Schneider, 2000).

The ability to vary water application along the main lateral of a center-pivot system based on position in the field allows the field manager to address specific soil and/or slope conditions and avoid areas of over- or under-irrigation, depending on preset management criteria. Thus, site-specific irrigation can potentially provide water conservation benefits in cases of overirrigation, erroneous irrigation scheduling, in-season precipitation harvesting, or inefficiencies associated with particular crop production practices (e.g., potatoes). Some examples of water conservation strategies under full ET conditions (minimal water stress throughout season) where site-specific applications are potentially able to reduce total water applied include:

- A major cause of excessive water applications can occur when dry areas appear in a center-pivot irrigated field; irrigators tend to run the irrigation systems longer and more often to ensure adequate water across the whole field. These poor management practices result in much of the area being overirrigated, and large amounts of water are wasted to compensate for suspected drought in relatively small areas. Site-specifically varying water applications can assist in addressing the management decisions that lead to localized, within-field drought and help conserve water, but they do not address the root causes.
- Water can also be conserved by applying less water to hillsides to reduce within-field runoff to low areas, to improve yields by eliminating water ponding in low areas, or to purposefully manage wet areas to reduce the extent of waterlogging problems.
- Water application amounts are generally high for the first span from the pivot point to the first tower even though application rates are low because it moves much more slowly than the outer towers. This area is typically either overwatered by as much as 20%, because the available nozzle selections do not allow for the correct application of water, or too dry since the nozzles are very small and prone to plugging. The often-wetted foliage in this area also has higher incidences of fungal diseases. One option is to turn off every other sprinkler along the first span for one or two rotations, and then turn on the sprinklers that are off and turn off the sprinklers that are on for one or two rotations. Another approach to eliminate both the overwatering and plugging problems within the first span area is to use relatively large nozzle sizes and site-specifically pulse the sprinklers on and off, applying the desired amount over time.
- Reduce or eliminate irrigation in wet areas in a field that develop from precipitation runoff, subsurface flow, high water table, springs, or unavoidable irrigation runoff.
- Manage soil water deficits on a spatial basis to maximize the opportunity to capture in-season precipitation in humid climates for subsequent use as crop evapotranspiration.
- The development of control and management technologies that can spatially and temporally direct the amount and frequency of appropriate agrochemical applications by site-specific self-propelled irrigation systems could also be very powerful tools that could increase productivity while reducing total water applications and minimizing adverse water quality impacts.

Some of the most common motives for growers to invest in advanced irrigation technologies are to: (1) reduce labor costs, (2) minimize water costs due to pumping (higher irrigation efficiencies), and (3) improve field-scale yields with better application uniformities. However, these reasons have not been economically justified and demonstrated by researchers and industry on SS-VRI systems for commercial crop production.

Site-specific sprinkler irrigation technologies and strategies are not a silver bullet for conserving water and energy; and they must also be integrated with other state-of-the-art farming technologies for maximum potential benefit. However, there is little information on possible approaches to managing these types of systems and their integration with other site-specific precision agriculture technologies for optimal water conservation that maximizes net returns to growers. Consequently, the large potential for water conservation with site-specific sprinkler irrigation is mostly unrealized.

State of the Art

At this time, the state of the art of site-specific sprinkler irrigation is that self-propelled center-pivot and linear-move sprinklers are definitely lacking in their intelligence capacity relative to most other industrial machine systems. The site-specific capabilities of self-propelled sprinkler systems have been slowly evolving over the past 30 years or more, starting with auto-reverse to avoid obstacles. Likewise, end gun controls to avoid watering roads, waterways, and buildings are very simple types of site-specific automation. The development of corner systems and guidance technologies (e.g., GPS, buried wire), which involve sequencing of sprinkler heads and irrigation of more complex field shapes, was another step forward in the automation of these machines. Manufacturers of self-propelled center-pivot sprinkler irrigation equipment also offer the ability to vary machine speed in triangle-shaped segments in as little as 2° increments to account for limited field variability, which changes the maximum application depths to match soil and crop conditions. However, field variability is not usually found in triangle-shaped parcels, and this represents a very coarse version of site-specific irrigation.

Support for addressing conditions within randomly shaped areas in the interior of a field (e.g., variable soil types, crop conditions) with commercially available equipment is quite limited. Current uses of site-specific sprinkler irrigation technologies for agricultural production are generally on a fairly coarse scale and limited to site-specific treatment based on physical features and non-cropped areas, such as waterways, ponds, buildings, roads, or rock outcrops, where some interior sprinkler heads are turned off in these areas (either 0% or 100% applications). Unfortunately, this is where the technology is likely to stay in the future until the cost-effectiveness can be increased by higher costs for water or the implementation of economic incentives for compliance with environmental and other regulations.

For several years, various manufacturers of this equipment have been offering limited site-specific capabilities for tertiary wastewater treatment and disposal, which apply water only to certain areas based on management maps for nitrogen and phosphorous or other potential contaminants. However, there has been relatively little commercial use of site-specific sprinkler irrigation technologies as a management tool for crop production. Starting in 2010, one manufacturer of self-propelled sprinkler irrigation machines began offering a site-specific variable-rate package as an option for agricultural systems, and other manufacturers are also starting to introduce similar site-specific sprinkler irrigation systems.

The design of a suitable site-specific irrigation system can be complex because of the need to address the causes of variation in each field, an assessment of the system capabilities needed to achieve the desired management level, constraints inherent in the existing equipment, and the philosophy of the owner/operator (decision support). These considerations are not mutually exclusive, but they do not lend themselves well to categorization. Design issues were discussed in more detail by Buchleiter et al. (2000), Evans et al. (2000), Sadler et al. (2000), and Perry et al. (2004).

Basically, more than 20 years of research, plus limited commercial availability of the technology since the mid-1990s, has resulted in very limited implementation of site-specific sprinkler irrigation by producers, implying that, for general agriculture, in many ways site-specific irrigation is currently a solution looking for a problem. Of course, there are some exceptions where these systems are used for implementing crop research on relatively small plots or for wastewater management with self-propelled sprinkler irrigation systems.

Evaluating Potential Benefits of Site-Specific Irrigation

A limited number of studies have been conducted to evaluate potential benefits of site-specific irrigation management (SSIM) in regard to profitability or water conservation. Most studies have used site-specific soil water balance simulations to estimate potential water savings, yields, or returns from SSIM compared to conventional uniform irrigation management (CUIM). The benefits of SSIM by definition will depend on site-specific soil conditions in conjunction with climatic conditions, as well as the crops grown and commodity prices. Universally, simulation studies have considered available water holding capacity (AWHC) as the site-specific soil parameter that determines irrigation management zone delineation. In-season precipitation is one factor that will likely influence how SSIM will be implemented and the resulting benefits. Studies to evaluate potential benefits of SSIM and profitability are discussed below and grouped based on the climatic conditions of the study: humid regions, and arid and semi-arid regions.

Humid Regions

Ritchie and Amato (1990) used a simulation approach and 30 years of climatic data to compare SSIM and CUIM water use and yield in a 4.6 ha study site delineated into management zones based on lowest, highest, and intermediate levels of AWHC. SSIM resulted in the best management option in terms of yield but not water use. Nijbroek et al. (2003) used a process-oriented crop model for soybeans to compare water use, drainage, and gross margin of SSIM versus CUIM for a 10 ha field site in Georgia that was delineated into five irrigation management zones based on AWHC. The simulation procedure was applied using 25 years of climatic data and the 10-year low market price for soybeans. Yield, water use, and leaching were not significantly different ($p \leq 0.05$) between SSIM and CUIM. Over the 25-year simulation period, SSIM tended to provide a \$16 ha^{-1} greater gross margin and reduced water use by 14% and drainage by 9% relative to CUIM based on the management zone with the lowest AWHC. However, SSIM did not result in the lowest water use or drainage relative to all the CUIM strategies evaluated. The increased cost of equipment, maintenance, and management associated with implementation of SSIM was not considered in computing gross margin. These costs would likely be greater than \$16 ha^{-1}; thus, CUIM would result in greater net return.

Oliveira et al. (2005) also used a simulation approach to evaluate the economic return of SSIM for tomatoes using microirrigation in Tennessee. The 16 ha study site had a 4:1 range in AWHC, and the simulation model used a calibrated model of tomato yield response to water. Based on 30 years of historical climate data, they found that CUIM using area-weighted AWHC to schedule irrigations versus SSIM arrangements with as many as five management zones did not require significantly different ($p \leq 0.05$) amounts of water. The CUIM strategy based on the soil with the lowest AWHC resulted in the highest net return but required 20% more water than SSIM. The cause of the greater water requirement of this CUIM strategy was not given.

Sadler et al. (2002) conducted a three-year field study to measure the mean yield response of corn to irrigation and compare variation in crop response within and among soil map units. Variation in crop response to irrigation was significant both between and among soil map units. Over the three-year study, the optimum irrigation amounts varied from 61% to 120% in space of the irrigation base rate, which was calculated as 100% of evapotranspiration minus precipitation. The three-year mean water savings for the field from the three strategies were 8% from actual practice, 19% from calculated perfect practice, and 21% from the yield-maximizing strategy. One conclusion of the study was that achieving optimum SSIM based on *a priori* information will be a significant challenge. Spatial variation in crop response to irrigation by year, soil map unit, and within soil map unit highlighted the need to use empirically derived site-specific crop response data to adequately simulate crop growth to SSIM in any economic analysis.

Lu et al. (2005) used the site-specific water response functions of Sadler et al. (2002) to evaluate the economic feasibility of SSIM for corn in South Carolina and concluded that SSIM was not profitable compared to CUIM. DeJonge et al. (2007) used a corn growth simulation model to evaluate yields and net returns of no irrigation, CUIM, and SSIM on a 20 ha study site in eastern Iowa. Irrigation management zones were delineated based on AWHC. The simulation model was calibrated using five years of yield data and used to estimate annual yield over 28 years using climatic data. The model predictions based on annual means were generally reasonable, but they were unable to model spatial variation. Consequently, the results showed that irrigation was profitable in only one of the 28 years, regardless of irrigation management strategy. Irrigation improved yield by 500 kg ha^{-1} in half of the years simulated, and SSIM showed slightly lower yields than CUIM. Irrigation reduced temporal variability in yield, and SSIM additionally reduced spatial variability in yield.

Al-Kufaishi et al. (2006) used a daily soil water balance model to simulate irrigation water use for a 7 ha field site with sugar beet in Germany under SSIM and CUIM. The simulation was conducted for one year having relatively low in-season precipitation. Irrigation management zones were delineated based on AWHC. Irrigation applications of 20, 30 and 40 mm were simulated. With 20 mm irrigation applications, SSIM used 13% less water than CUIM. Water savings with SSIM was from increased utilization of stored soil moisture and in-season precipitation.

Hedley and Yule (2009) used a soil water balance simulation on a site-specific basis to evaluate irrigation water use between SSIM and CUIM on 156 ha pasture and 53 ha corn field sites in New Zealand. Irrigation management zones were delineated based on correlations between measured apparent soil electrical conductivity and AWHC. Water use under SSIM was reduced 20% to 26% relative to CUIM over a three-year simulation period. Water savings under SSIM were from increased utilization of stored soil moisture and in-season precipitation and restricted drainage in one management zone of the 53 ha corn field site. Hedley et al. (2009) used the same soil water balance simulation to evaluate irrigation water use between SSIM and CUIM on 40 ha pasture, 24 ha potato, and 22 ha corn sites in New Zealand. Annual water use under SSIM was reduced 9% to 19% and drainage was reduced 25% to 45% relative to CUIM.

Arid and Semi-Arid Regions

Marek et al. (2001) conducted an economic analysis of SSIM using site-specific yield data from 15,000 ha in the northern Texas High Plains. They concluded that small improvements in yield from SSIM would be required to justify adoption of SSIM. How SSIM was to be used to improve yield was not identified but was assumed possible. Watkins et al. (2002) used a simulation approach to evaluate the economic and environmental benefits of SSIM for seed potatoes in Idaho. They concluded that SSIM was more likely to be both economically and environmentally beneficial than variable-rate nitrogen application for the study conditions. However, the simulation model was not calibrated to simulate nitrogen losses, and neither yield nor nitrogen loss predictions were validated. Sensitivity analysis of the results showed that a small increase in estimated costs for SSIM over CUIM would result in the latter being more economical. King et al. (2006) used a center-pivot system equipped for site-specific water application to compare SSIM and CUIM on an 11.5 ha field site of potatoes in Idaho over a two-year period. Irrigation management treatments were randomly assigned to 18 plots across half the field site in each year. Half the plots received SSIM, and the remainder received CUIM. There was no significant difference in yield or water use between SSIM and CUIM.

The results from studies to evaluate potential benefits from SSIM have predicted water savings ranging from 0% to 26%. All studies have ignored timing limitations for site-specific water applications imposed by the irrigation system and assumed perfect knowledge of crop water response functions, crop evapotranspiration, and soil characteristics. In the case of SSIM with center-pivot sprinkler systems, the irrigation system cannot be everywhere in the field instantaneously, which is assumed in simulation studies. There can be days between irrigation opportunities with real irrigation systems. In practice, the lack of perfect knowledge and irrigation system limitations will likely result in water savings less than those predicted by simulation studies. Economic studies linking water use to yield response have generally found SSIM not to be profitable. This may result from the fact that yield response to the water curve near maximum yield (100% evapotranspiration) is almost flat, so that small changes in water applied using SSIM have little effect on yield. In addition, maximizing yield per unit or area is basically encouraged by the low prevailing cost of water, except in cases where regulatory constraints exist.

The majority of studies conducted to evaluate potential benefits of SSIM have been conducted under humid climatic conditions. In locations where in-season precipitation can often occur, the potential exists to reduce irrigation water application with SSIM by repeated depletion of available soil water storage and more efficient capture of in-season, non-uniform precipitation for crop evapotranspiration. This opportunity is generally limited or nonexistent in arid and semi-arid locations. Ironically, SSIM may have greater relative potential to reduce irrigation water use in humid climates when irrigating for maximum yield (100% evapotranspiration).

Barriers to Adoption

There are several barriers to adoption of site-specific sprinkler irrigation with self-propelled machines. It seems that the main reason that site-specific sprinkler irrigation has not generally been a commercial success to date is the lack of a market because cost-effectiveness has not been demonstrated for crop production, although limited water supplies for irrigation in some areas are driving some interest. Technology has not been a limiting factor.

The amount of water that can be conserved by improved irrigation systems and practices depends on the ability of a particular type of irrigation system to implement improved management. Currently, however, less than optimal management levels are limiting the technology, which is primarily due to the lack of appropriate economic and social incentives to fully implement the improved practices to their optimum levels.

As is the case with most PA technologies, economic risk may also be increased with the adoption of the technology (Gandonou and Dillon, 2003; Lambert and Lowenberg-DeBoer, 2000). There are several possible reasons for this problem, which include:

- The very low adoption rate can be partially attributed to a lack of public and private research demonstrating that SS-VRI will conserve water and/or increase net returns for crop production. This is particularly true when considering the use of site-specific irrigation in combination with other precision, site-specific agriculture technologies. However, public funding for these types of research has been declining rapidly over the past several decades.

- The inability of producers to pass costs on to the consumer, the generally low rate of return on investment of SS-VRI on broad acre crops, and management inputs are high for SS-VRI systems.
- Maintenance requirements and costs may be increased with the additional valves, wires, hoses, panels, and other equipment needed for SS-VRI, particularly for pulse-modulation systems (high-frequency operation) based on costs for long-term research machines.
- Dealers do not generally embrace these technologies because they do not see opportunities for profit and they are afraid of creating a servicing nightmare for themselves.
- Government regulatory and action agencies generally do not support these technologies for cost-share and other farm programs, especially at the local level, which may be partially related to the lack of research demonstrating benefits.
- General, broad-based, and easily modified software for managing SS-VRI systems (decision support) is not available for a multitude of crops, climatic conditions, topography, and soil textures.
- There is a severe shortage of available agronomic expertise to set up and maintain decision support software for each field (English, 2010). Growers usually do not have the inclination, knowledge, or time to learn and periodically update and adjust complex software; thus, dealers or consultants would likely have to provide this service. Specialized, continual training on the hardware, software, and advanced agronomic principles is needed for dealers, technicians, and other personnel to properly service these systems.
- Improving water productivity and irrigation efficiencies will require substantial investments by farmers and others in infrastructure and new equipment. Such investments are often accompanied by higher operating costs and may require greater management skills to be sustainable.
- Irrigators will also need the flexibility to manage the rate, frequency, and duration of water supplies over time to economically and environmentally optimize allocation of limited water and other inputs among crops on their farms, which can be a major problem with many surface water supply and delivery systems.

Servicing the hardware and control software on advanced, integrated systems can be difficult for dealers. Some of this concern can be addressed with more training of technicians and service personnel. However, much of the service load can be removed from the dealers by using the internet for remote hardware and software troubleshooting by the manufacturer or consultants at a central location, and identified defective parts, computer cards, or chips can be changed by on-site technicians. However, this is not yet an available option in most situations.

There is a definite shortage of decision support applications (software) and associated analysis tools for any aspect of site-specific sprinkler irrigation. None of the existing decision support systems focus on maximizing net returns, although some may provide basic parts of the necessary information. It is highly probable that the scarcity of decision support programs of any type is largely due to the potential liability inherent in any decision support system, which unfortunately will likely remain a concern. Every decision support application would have to be tailored to fit each individual field, and mistakes can have costly consequences for which manufacturers and service providers are understandably unwilling to assume responsibility. In addition, development of suitable decision making tools must consider that their potential complexity may also present barriers to adoption that must be addressed.

Use of SS-VRI to avoid irrigating waterways, roads, etc., may be economical in terms of water and nutrient savings as well as avoidance of environmental and regulatory penalties. However, the economics of SS-VRI for general crop production is a major concern because the savings in water are typically only on the order of 5% to 10% over more conventional management in arid areas (Evans et al., 1996) but may be as high as 26% in humid regions (Hedley and Yule, 2009).

Higher net returns to the grower may be needed to economically justify the capital costs of implementing site-specific irrigation management with center pivots (about \$300 to \$550 ha^{-1} additional, depending on size and options, over CUIM systems) plus the extra mapping and management costs. Operating costs may be higher as well because of added maintenance of sensors stations, communications, software maintenance, and consultant fees. Thus, the marginal costs are high for the relatively small water savings.

KNOWLEDGE GAPS

Almost all of the SS-VRI research done to date has been directed toward development and improvement of hardware and basic control software. Little research has been done on the economics, determination of the number of zones or sectors, or the management of these systems for greatest agronomic benefit. Past research was generally directed toward meeting full crop ET and maximizing yields per unit area with no concern for limited water availability scenarios. Likewise, there has been no research considering the use of SS-VRI in combination with other precision (site-specific) agriculture technologies, which will be critical in establishing the long-term cost-effectiveness of these systems for crop production. In addition, none of the existing decision support systems used with center-pivot and linear-move sprinkler irrigation systems focuses on maximizing net returns, although some of these tools may provide parts of the necessary information. These types of research need to be conducted before the full potential of these technologies can be commercially realized.

There are several significant research areas that will be required to address the barriers and needs discussed above. Solving these issues will require the continued refining of water conservation measures, including improved water productivity of irrigation systems and increased net profitability. Information is needed for both humid and arid climates because the management alternatives and techniques may differ. However, developing these answers in a timely manner is a major concern in an era of steadily decreasing public funding for field-based agricultural cropping systems research. Some of these knowledge gaps are discussed below.

There is no information or guidelines to assist consultants and growers in defining management areas or writing prescriptions for cost-effective, site-specific sprinkler irrigation management. Even basic decision support programs are lacking in this arena.

There is a pressing need for research that documents and predicts the impact of managed drought stress on crop production (Oswald et al., 2005; Evans and Sadler, 2008). There is a considerable body of research relating soil salinity to crop yield, but there is much less information available on how other biotic and abiotic factors affect crop ET. Much additional information is required about the actual crop ET (ET_a) levels when plants experience different levels of stress during different growth stages of both major and minor annual crops in managed soil water deficits. Can we predict water production functions for various soil water deficits, and are they static or growing season dependent? This needed research has not been done because of the expense as well as the complexity of the interactions with other factors that also affect ET_a. The long-term effect of managed and unmanaged deficit irrigations on many perennial crops also needs more research to ensure sustainability. Conversely, under full irrigation, it is generally assumed that ET can vary in space and time across a field, but it is not known if addressing this variation actually results in significant water savings.

One way to increase economic incentives that encourage adoption is to add value to the irrigation system by accomplishing additional tasks with little additional cost, such as site-specific chemigation (Watkins et al., 1998; King et al., 2009). Research is needed in this regard to develop and test novel uses of the technology, such as optimizing chemigation, minimizing soil erosion, managing the area under individual spans over several irrigation events to minimize surface redistribution of water (runoff), and identifying other potential benefits.

The full promise of these technologies is limited by the ability to economically and remotely monitor soil moisture content or plant water status in specific areas within a field over time. It is not known how to best locate various combinations of wireless sensors for maximum benefit across a field. The necessary knowledge and software for the integration of diverse distributed and mobile sensor networks plus other types of remote sensing for dynamic closed-loop adaptive control have not been developed.

Another major research need is to integrate other site-specific precision agriculture technologies with site-specific irrigation water management. This includes the development of more efficient methods of site-specifically applying crop amendments (e.g., nutrients, pesticides) with chemigation and other methods that will reduce the amount of agrochemicals used per hectare, improve profit margins, and reduce environmental impacts. How does site-specific irrigation interact in combination with other site-specific agriculture technologies? In addition, there is a shortage of reliable, low-cost, variable-rate water application devices.

Deficit Irrigation

Increasing crop productivity while reducing the amount of applied water implies that producers will often be managing irrigations under severe to moderate soil water deficit conditions (drought) in either time or space during at least part of the growing season. This is often referred to as managed deficit irrigation, which can have many forms. Managed deficit irrigation strategies have the potential to conserve more water with less impact on yields than any other alternatives when implemented correctly (Bras and Cordova, 1981; English et al., 1990; English et al., 2002; Zhang, 2003; Fereres and Soriano, 2006; Evans and Sadler, 2008; Geerts and Raes, 2009; Rodrígues and Pereira, 2009).

The intention is to economically optimize production for each unit of water applied. The most common deficit irrigation strategy is to manage reduced water supplies to be able to adequately irrigate only at specific growth stages throughout the season, which can result in water savings of 5% to 50%. Total yields of some annual crops may be reduced 10% to 30% due to these managed drought stresses depending on irrigation system upgrades and management (English, 1990; English et al., 2002; Klocke et al., 2004, 2007; Payero et al., 2005, 2006; Lamm et al., 2008). The concept applies to drip and sprinkler irrigation as well as site-specific irrigation management in both humid and arid climates.

Site-specific variable-rate sprinkler irrigation could play a major role in maximizing net returns when implementing limited or deficit irrigation strategies in water-short areas. These strategies can potentially conserve large amounts of water on the types of crops generally irrigated with self-propelled sprinkler systems where actual ET conditions may be considerably less than optimal.

However, economic risk to growers is greatly increased under deficit irrigation, and yet it is quite likely that production costs will not decrease in proportion to the decreased water supply. Even though other inputs may also be reduced (e.g., nutrients) due to the lower yield goals, management costs will likely increase. Thus, deficit irrigation strategies will require substantial investment in improved irrigation technologies and management to be successful (Klocke et al., 2004, 2007; Payero et al., 2005, 2006; Evans and Sadler, 2008; Lamm et al., 2008).

High-value crops (e.g., vine and tree crops) may also produce significant water savings per unit area through various deficit irrigation strategies with little impact on final yields, but their total impact will be much lower because they generally occupy less than 10% of the total irrigated area (location-specific) and will likely utilize microirrigation methods (McCarthy et al., 2000; Fereres and Soriano, 2006; Evans and Sadler, 2008). Different crops will have different allowable deficit levels and timing tolerances, and optimal deficit irrigation strategies must be developed for most crops, with the most pressing need for low-value field crops (including bioenergy crops). Future research must include ways to match crop/plant needs with inputs over time, adjusting plant populations for various drought levels, figuring out when stress is most easily tolerated with the least yield loss, and developing means to minimize pest issues to below economic thresholds. Advanced irrigation scheduling techniques to better manage in both time and space will be required.

Decision Support Systems

Specialized software programs, commonly called decision support systems (DSS, also called decision making systems), need to be developed for site-specific irrigation systems. These systems take advantage of real-time environmental and crop status data from multiple sources and can greatly assist irrigators in reducing unnecessary expenses and improving water productivity to the largest extent possible (McCarthy et al., 2010). Future DSS programs should use holistic approaches to irrigated crop management, which require seamless integration of the hardware (physical system), existing control and safety mechanisms, and positioning systems (i.e., GPS).

The DSS should consider the amount of water to apply based on seasonal timing, yield potential, crop and water prices, etc., in order to maximize net return rather than total yield, as currently practiced. Closed-loop model-predictive adaptive control approaches embedded in the DSS need to interface with crop and pest models and other software tools, wireless field data networks, and other remotely sensed data for automated decision making. The various components of a decision-making program should also have some abilities to be self-calibrating and self-learning so that the system can automatically adjust to changing conditions for effective adaptive control. However, broad-based and easily modified DSS software for managing site-specific sprinkler irrigation systems for optimal crop production is not available for a multitude of crops, climatic conditions, topography, and soil textures.

CONCLUSIONS

Agriculture will need to increase crop production to meet future societal needs in spite of two major constraints, which are that the productive irrigated land base and the quantity of available water are both declining sharply. Energy availability will also be limited. Major adjustments will have to be made in both agrarian and urban settings to meet these needs. Both urban and rural users will have to adjust their expectations on how and where water will be used. Society may have to accept much higher water and energy costs, which, in turn, may result in substantially higher food costs. Technology has not been the limiting factor.

There is little doubt that irrigated agriculture can reduce its water use while maintaining reasonable production levels. However, the challenges are substantial. Novel and improved strategies and practices are needed to increase the cost-effectiveness of crop production, reduce soil erosion, reduce energy requirements, and reduce surface and groundwater contamination from agricultural lands, as well as sustain national food production for strategic, economic, and social benefits. Changes in existing water policies and institutional structures will also be needed to enable and foster emerging water conservation technologies. The use of self-propelled sprinkler irrigation is expected to increase around the world as a cost-effective means to satisfy many of these often-competing goals.

Existing irrigation technologies are well advanced and would conserve large amounts of water if fully implemented to their potential. The amount of water that can be conserved by improved irrigation systems and practices depends on the ability of a particular type of irrigation system to implement improved management practices. Currently, however, there are few incentives for the higher levels of management that are required, which is limiting the technology. The resulting less-than-optimal levels of irrigation management are primarily due to the lack of appropriate economic and social incentives to adopt the improved practices.

Irrigation management will also benefit from combining other existing precision agriculture technologies, such as site-specific nutrient and pesticide applications, into comprehensive management systems for irrigated agriculture. Alternative management and cultural practices must be combined into holistic, sustainable management systems, which will require the simultaneous development and integration of: (1) improved irrigation application technologies, (2) broad implementation of managed deficit irrigation of most irrigated crops, and (3) development of integrated decision support systems. It will also be mandatory to implement system-wide enhancements of water delivery systems and other supporting monitoring, modeling, and control technologies to enable the adoption and use of deficit irrigation and advanced irrigation technologies.

The development of more efficient water management systems and strategies to improve crop water productivity and support a sustainable agricultural environment will be required. In addition, innovative crop production strategies will have to target inputs to meet yield goals somewhere near the economic optimum (e.g., deficit irrigation management), which will generally be considerably less than conditions of full crop ET for maximum yields. It is expected that variable-rate chemigation will be increasingly common in the future, but much of the needed research base is lacking.

There are several other options for conserving water in irrigated agriculture, including conversion to LEPA nozzles and reducing or eliminating the use of end guns on self-propelled center-pivot and linear-move sprinkler systems. Controlled applications of water can potentially be managed on a spatial basis according to estimated crop need, stage of growth, variety, topography, and other criteria. Optimal use of available precipitation will obviously be required. However, carefully managed deficit irrigation of agronomic crops provides the greatest potential for substantially reducing agricultural water use because of the larger land areas that are involved. High-value crops may also produce significant water savings per unit area through various deficit irrigation strategies, but their total impact will be much lower because they generally occupy less than 10% of irrigated area (location-specific) and will likely utilize microirrigation methods.

Nonetheless, managed deficit irrigation strategies still must be developed for most food and other crops in different growing regions. Many of the tools to implement managed deficit irrigation strategies with self-propelled sprinkler systems are already available, although substantial research efforts are needed to derive their maximum potential and establish management criteria. Site-specific sprinkler and microirrigation systems will undoubtedly play major roles in the research programs that develop advanced, deficit irrigation management strategies.

Integrated, comprehensive decision support tools will be needed to assist growers and managers in optimizing the allocation of limited water among crops. These programs should use holistic approaches that not only include the amount of water to apply at specific times in the growing season but also the yield potential, crop price, cost of operations, and other economic factors on a whole-farm scale in order to maximize net return to the producer rather than total yield.

The implementation of site-specific irrigation technologies that can spatially direct the amount and frequency of water (and appropriate agrochemical) applications could potentially be very powerful tools to increase water productivity, reduce inputs, and minimize adverse water quality impacts. However, more than 20 years of public and private research has lead to limited adoption of these technologies, mostly because their cost-effectiveness for crop production has never been demonstrated. Thus, it is time to move from developing hardware to research directed at developing and documenting cost-effective, site-specific water conservation strategies.

Site-specific, deficit irrigation strategies with self-propelled sprinkler systems combined with other relevant site-specific precision agriculture technologies are expected to play major parts in this technological revolution. However, in this era of declining field research on cropping systems, a large amount of work is urgently needed to determine the specific knowledge and technologies required to accomplish sustainable production under conditions of declining resource availability.

References

Al-Kufaishi S. A., B. S. Blackmore, and H. Sourell. 2006. The feasibility of using variable-rate water application under a central-pivot irrigation system. *Irrig. and Drain. Sys*. 20(3): 317-327.

Andrade-Sánchez, P., F. J. Pierce, and T. V. Elliott. 2007. Performance assessment of wireless sensor networks in agricultural settings. ASABE Paper No. 073076. St. Joseph, Mich.: ASABE.

Bras, R. L., and J. R. Cordova. 1981. Intraseasonal water allocation in deficit irrigation. *Water Resources Res.* 17(4): 866-874.

Buchleiter, G. W., C. Camp, R. G. Evans, and B. A. King. 2000. Technologies for variable water application with sprinklers In *Proc. 4th Decennial Natl. Irrigation Symp*., 316-321. R. G. Evans, B. L. Benham, and T. P. Trooien, eds. St. Joseph, Mich.: ASAE.

Camp, C. R., and E. J. Sadler. 1994. Center-pivot irrigation system for site-specific water and nutrient management. ASAE Paper No. 941586. St. Joseph, Mich.: ASAE.

Camp, C. R., Y.-C. Lu, and E. J. Sadler. 2002. Spatial variation in crop response: Part 2. Implications for water and nitrogen management. In *Proc. 2002 Irrigation Association Intl. Exposition and Technical Conf.* Falls Church, Va.: Irrigation Association.

Chávez, J. L., F. J. Pierce, T. V. Elliott, and R. G. Evans. 2010a. A remote irrigation monitoring and control system (RIMCS) for continuous-move systems: Part A. Description and development. *Precision Agric.* 11(1): 1-10.

Chávez, J. L. F. J. Pierce, T. V. Elliott, R. G. Evans, Y. Kim, and W. M. Iversen. 2010b. A remote irrigation monitoring and control system (RIMCS) for continuous-move systems: Part B. Field testing and results. *Precision Agric.* 11(1): 11-26.

Chávez, J. L., F. J. Pierce, and R. G. Evans. 2010c. Compensating inherent linear-move water application errors using a variable-rate irrigation system. *Irrig. Sci.* 28(3): 203-210.

Clemmens, A., and R. Allen. 2005. Impact of agricultural water conservation on water availability. In *Proc. World Water and Environ. Resources Congress*. Reston, Va.: ASCE.

DeJonge, K. C., A. L. Kaleita, and K. R. Thorp. 2007. Simulating the effects of spatially variable irrigation on corn yields, costs, and revenue in Iowa. *Agric. Water Mgmt.* 92(1-2): 99-109.

Duke, H. R., D. F. Heermann, and C. W. Fraisse. 1992. Linear-move irrigation system for fertilizer management research. In *Proc. 1992 Irrigation Association Intl. Exposition and Technical Conf.*, 72-81. Falls Church, Va.: Irrigation Association.

Dukes, M. D., and C. D. Perry. 2006. Uniformity testing of variable-rate center-pivot irrigation control systems. *Precision Agric.* 7(1): 205-218.

English, M. J. 1990. Deficit irrigation: Observations in the Columbia basin. *J. Irrig. and Drain. Eng*. 116(3): 413-426.

English, M. J. 2010. A developing crisis in irrigation advisory services. ASABE Paper No. IRR109595. In *Proc. 5th Decennial Natl. Irrigation Symp.* M. Dukes, ed. St. Joseph, Mich.: ASABE.

English, M. J., J. T. Musick, and V. V. N. Murty. 1990. Deficit irrigation. In *Management of Farm Irrigation Systems*, 631-663. G. J. Hoffman, T. A. Howell, and K. H. Solomon. St. Joseph, Mich.: ASAE.

English, M. J., K. H. Solomon, and G. J. Hoffman. 2002. A paradigm shift in irrigation management. *J. Irrig. and Drain. Eng.* 128(5): 267-277.

Evans, R. G., and G. B. Harting. 1999. Precision irrigation with center-pivot systems on potatoes. In *Proc. 1999 ASCE Intl. Water Resources Eng. Conf.* R. Walton and R. E. Nece, eds. Reston, Va.: ASCE.

Evans, R. G., and E. J. Sadler. 2008. Methods and technologies to improve efficiency of water use. *Water Resources Res*. 44(2): W00E04.

Evans, R. G., S. Han, S. M. Schneider, and M. W. Kroeger. 1996. Precision center-pivot irrigation for efficient use of water and nitrogen. In *Proc. 3rd Intl. Conf. on Precision Agriculture*, 75-84. P. C. Robert, R. H. Rust, and W. E. Larson, eds. Madison, Wisc.: ASA-CSSA-SSSA.

Evans, R. G., G. W. Buchleiter, E. J. Sadler, B. A. King, and G. B. Harting. 2000. Controls for precision irrigation with self-propelled systems. In *Proc. 4th Decennial National Irrigation Symp*., 322-331. R. G. Evans, B. L. Benham, and T. P. Trooien, eds. St. Joseph, Mich.: ASAE.

Evans, R. G., W. M. Iversen, W. B. Stevens, and J. D. Jabro. 2010. Development of combined site-specific MESA and LEPA methods on a linear-move sprinkler irrigation system. *Applied Eng. in Agric.* 26(5): 883-895.

FAO. 2010. State of world food insecurity in the world: 2010. Rome, Italy: UN Food and Agriculture Organization.

Farahani, H. J., D. L. Shaner, G. W. Buchleiter, and G. A. Bartlett. 2006. Evaluation of a low-volume agro-chemical application system for center-pivot irrigation. *Applied Eng. in Agric.* 22(4): 517-528.

Fereres, E., and A. Soriano. 2006. Deficit irrigation for reducing agricultural water use. *J. Exp. Botany* 58(2): 147-159.

Fraisse, C. W., D. F. Heermann, and H. R. Duke. 1992. Modified linear-move system for experimental water application. In *Proc. Advances in Planning, Design, and Management of Irrigation Systems as Related to Sustainable Land Use*, 1: 367-376. J. Jeyen, E. Mwendera, and M. Badji, eds. Leuven, Belgium: Center for Irrigation Engineering.

Gandonou, J.-M., and C. R. Dillon. 2003. Precision agriculture, whole field farming, and irrigation practices: A financial risk analysis. In *Proc. 2003 American Agricultural Economics Association Annual Meeting*. Paper No. 22078. Milwaukee, Wisc.: Agricultural and Applied Economics Association.

Geerts, S., and D. Raes. 2009. Deficit irrigation as an on-farm strategy to maximize crop water productivity in dry areas. *Agric. Water Mgmt*. 96(9): 1275-1284.

Han, S., S. M. Schneider, R. G. Evans, and S. L. Rawlins. 1996. Spatial variability of soil properties on two center-pivot irrigated fields. In *Proc. 3rd Annual Intl. Conf. on Precision Agriculture*, 97-106. Madison, Wisc.: ASA-CSSA-SSSA.

Han, Y. J., A. Khalilian, T. O. Owino, H. J. Farahani, and S. Moore. 2009. Development of Clemson variable-rate lateral irrigation system. *Comp. and Elec. in Agric.* 68(1): 108-113.

Hedley, C. B., and I. J. Yule. 2009. Soil water status mapping and two variable-rate irrigation scenarios. *Precision Agric*. 10(4): 342-355.

Hedley, C. B., I. J. Yule, M. P. Tuohy, and I. Vogeler. 2009. Key performance indicators for simulated variable-rate irrigation of variable soils in humid regions. *Trans. ASABE* 52(5): 1575-1584.

Khan, S., R. Tariq, C. Yuanlai, and J. Blackwell. 2006. Can irrigation be sustainable? *Agric. Water Mgmt.* 80(1-3): 87-99.

Kim, Y., and R. G. Evans. 2009. Software design for wireless sensor-based site-specific irrigation. *Comp. and Elect. in Agric.* 66(2): 159-165.

Kim, Y., R. G. Evans, and W. M. Iversen. 2008. Remote sensing and control of an irrigation system using a wireless sensor network. *IEEE Trans. Instrum. and Meas.* 57(7): 1379-1387.

Kim, Y., R. G. Evans, and W. M. Iversen. 2009. Evaluation of closed-loop site-specific irrigation with wireless sensor network. *ASCE J. Irrig. and Drain. Eng*. 135(1): 25-31.

King, B. A., R. A. Brady, I. R. McCann, and J. C. Stark. 1995. Variable-rate water application through sprinkler irrigation. In *Proc. Site-Specific Management for Agriculture Systems*, 485-493. P. C. Robert, R. H. Rust, and W. E. Larson, eds. Madison, Wisc.: ASA-CSSA-SSSA.

King, B. A., J. C. Stark, and R. W. Wall. 2006. Comparison of site-specific and conventional uniform irrigation management for potatoes. *Applied Eng in Agric*. 22(5): 677-688.

King, B. A., R. W. Wall, and T. F. Karsky. 2009. Center-pivot irrigation system for independent site-specific management of water and chemical applications. *Applied Eng. in Agric*. 25(2): 187-198.

Klocke, N. L., J. P. Schneekloth, S. R. Melvin, R. T. Clark, and J. O. Payero. 2004. Field-scale limited irrigation scenarios for water policy strategies. *Applied Eng. in Agric.* 20(5): 623-631.

Klocke, N. L., J. O. Payero, and J. P. Schneekloth. 2007. Long-term response of corn to limited irrigation and crop rotations. *Trans. ASABE* 50(6): 2117-2124.

Kranz, W. 2009. Monitoring irrigation water applications with computerized controllers. In *Proc. 21st Annual Central Plains Irrigation Conf.* Colby, Kans.: Central Plains Irrigation Association.

Kranz, W. L., R. G. Evans, F. R. Lamm, S. A. O'Shaughnessy, and T. R. Peters. 2010. A review of center-pivot irrigation control and automation technologies. Paper No. IRR109632. In *Proc. 5th Decennial Irrigation Symposium*. M. D. Dukes, ed. St. Joseph, Mich.: ASABE.

Lamm, F. R., R. M. Aiken, and A. A. Abou Kheira. 2008. Effect of tillage practices and deficit irrigation on corn. In *Proc. 20th Central Plains Irrigation Conf.* Colby, Kansas: Central Plains Irrigation Association.

Lambert, D., and J. Lowenberg-DeBoer. 2000. Precision agriculture profitability review. West Lafayette, Ind.: Purdue University, Site-Specific Management Center. Available at: www.agriculture.purdue.edu/ssmc/frames/newsoilsx.pdf. Accessed 11 April 2011.

Lu, Y.-C., E. J. Sadler, and C. R. Camp. 2005. Economic feasibility study of variable irrigation of corn production in southeast coastal plain. *J. Sust. Agric.* 26(3): 69-81.

McCann, I. R., B. A. King, and J. C. Stark. 1997. Variable-rate water and chemical application for continuous-move sprinkler irrigation systems. *Applied Eng. in Agric*. 13(5): 609-615.

McCarthy, M. G., B. R. Loveys, P. R. Dry, and M. Stoll. 2000. Regulated deficit irrigation and partial root zone drying as irrigation management techniques for grapevines. In *Deficit Irrigation Practices*, 79-87. Water Reports 22. Rome, Italy: UN Food and Agricultural Organization.

McCarthy, A. C., N. H. Hancock, and S. R. Raine. 2010. VARIwise: A general-purpose adaptive control simulation framework for spatially and temporally varied irrigation at sub-field scale. *Comp. and Elect. in Agric*. 70(1): 117-128

Marek, T., E. Cox, L. Almas, and S. Amosson. 2001. The feasibility of variable-rate irrigation with center-pivot systems in the northern Texas High Plains. ASAE Paper No. 011117. St. Joseph, Mich.: ASAE.

Miranda, F. R., R. E. Yoder, and J. B. Wilkerson. 2003. A site-specific irrigation control system. ASAE Paper No. 031129. St. Joseph, Mich.: ASAE.

Nijbroek, R., G. Hoogenboom, and J. W. Jones. 2003. Optimizing irrigation management for a spatially variable soybean field. *Agric. Sys.* 76(1): 359-377.

Oliveira, C., R. E. Yoder, and J. Larson. 2005. Evaluating the returns to site-specific irrigation. In *Proc. 7th Intl. Conf. on Precision Agriculture*. D. J. Mulla, ed. St. Paul, Minn.: Precision Agriculture Center, University of Minnesota.

Omary, M., C. R. Camp, and E. J. Sadler. 1997. Center-pivot irrigation system modification to provide variable water application depths. *Applied Eng. in Agric.* 13(2): 235-239.

O'Shaughnessy, S. A., and S. R. Evett. 2010. Developing wireless sensor networks for monitoring crop canopy temperature using a moving sprinkler system as a platform. *Applied Eng. in Agric.* 26(2): 331-341.

Oswald, J. K., H. D. Werner, and T. P. Trooien. 2005. Automated water management for center-pivot irrigation systems. In *Proc. 2005 Irrigation Association Intl. Exposition and Technical Conf.*, 349-356. Falls Church, Va.: Irrigation Association.

Palacin, J., J. A. Salse, X. Slua, J Arno, R. Blanco, and C. Zanuy. 2005. Center-pivot automation for agrochemical use. *Comp.*

and Elect. in Agric. 49(3): 419-430.
Payero, J. O., S. R. Melvin, and S. Irmak. 2005. Response of soybean to deficit irrigation in the semi-arid environment of west-central Nebraska. *Trans. ASAE* 48(6): 2189-2203
Payero, J. O., S. R. Melvin, S. Irmak, and D. Tarkalson. 2006. Yield response of corn to deficit irrigation in a semiarid climate. *Agric. Water Mgmt*. 84(1-2): 101-112.
Pereira, L. S., I. Cordery, and I. Acovides. 2002. Coping with water scarcity. IHP-VI, 406 Technical Documents in Hydrology, No. 58. Paris, France: UNESCO.
Perry, C. D., S. Pocknee, and O. Hansen. 2003. Variable-rate irrigation. *Resource* 10(1): 11-12. St. Joseph, Mich.: ASAE.
Perry, C. D., M. D. Dukes, and K. A. Harrison. 2004. Effects of variable-rate sprinkler cycling on irrigation uniformity. ASAE Paper No. 041117. St. Joseph, Mich.: ASAE.
Pierce, F. J., J. L. Chavez, T. V. Elliott, G. R. Matthews, R. G. Evans, and Y. Kim. 2006. A remote real-time continuous-move irrigation control and monitoring system. ASABE Paper No. 062162. St. Joseph, Mich.: ASABE.
Postel, S. 1999. *Pillar of Sand: Can the Irrigation Miracle Last?* New York, N.Y.: Worldwatch Books, W.W. Norton and Co.
Ritchie, J. T., and M. Amato. 1990. Field evaluation of plant extractable soil water for irrigation scheduling. *Acta Horticulturae* 278: 595-615.
Rodrigues, G. C., and L. S. Pereira. 2009. Assessing economic impacts of deficit irrigation as related to water productivity and water costs. *Biosystems Eng.* 103(4): 536-551.
Roth, R. L., and B. R. Gardner. 1989. Modified self-moving irrigation system for water-nitrogen crop production studies. ASAE Paper No. 890502. St. Joseph, Mich.: ASAE.
Sadler, E. J., R. G. Evans, G. W. Buchleiter, B. A. King, and C. R. Camp. 2000. Site-specific irrigation management and control. In *Proc. 4th Decennial National Irrigation Symp.*, 304-315. R. G. Evans, B. L. Benham, and T. P. Trooien, eds. St. Joseph, Mich.: ASAE.
Sadler, E. J., C. R. Camp, D. E. Evans, and J. A. Millen. 2002. Spatial variation of corn response to irrigation. *Trans. ASAE* 45(6): 1869-1881.
Sadler, E. J., R. G. Evans, K .C. Stone, and C. R. Camp. 2005. Opportunities for conservation with precision irrigation. *J. Soil and Water Cons.* 60(6): 371-379.
Schneider, A. D. 2000. Efficiency and uniformity of LEPA and spray spinner methods: A review. *Trans. ASAE* 43(4): 937-944
Schütze, N., and G. H. Schmitz. 2009. A neuro-dynamic programming approach for optimal scheduling and feedback control of deficit irrigation systems. In *Proc. European Geoscience Union General Assembly 2009*. Munich, Germany: European Geosciences Union. Available at: http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.149.2226&rep=rep1&type=pdf. Accessed 27 June 2011.
Solomon, K., and M. Kodoma. 1978. Center pivot end sprinkler pattern analysis and selection. *Trans. ASAE* 21(4): 706-712.
Spears, T. D. 2003. Irrigating efficiently to feed the world in 2050. In *Proc. 2003 Irrigation Association Intl. Exposition and Technical Conf*., 411-422. Falls Church, Va.: Irrigation Association.
Stone, K. C., R. G. Hunt, K. B. Cantrell, and K. S. Ro. 2010. The potential impacts of biomass feedstock production on water resource availability. *Bioresource Tech.* 101(6): 2014-2025.
Sumner, H. R., P. M. Garvey, D. F. Heermann, and L. D. Chandler. 1997. Center-pivot irrigation attached sprayer. *Applied Eng. in Agric.* 13(3): 323-327.
USDA-NASS. 2009. Table 4: Land irrigated by method of water distribution, 2008 and 2003. In *Census of Agriculture: 2008 Farm and Ranch Irrigation Survey.* Washington, D.C.: USDA National Agricultural Statistic Service.
Watkins, K. B., Y. C. Lu, and W. Y Huang. 1998. Economic and environmental feasibility of variable-rate nitrogen fertilizer application with carry-over effects. *J. Agric. and Res. Econ.* 23(2): 401-426.
Watkins, K. B., Y.-C. Lu, and W.-Y. Huang. 2002. A case study of economic and environmental impact of variable-rate nitrogen and water application. *Agric. Eng. J.* 11(4): 173-185.
Zhang, H. 2003. Chapter 19: Water productivity in agriculture: Limits and opportunities for improvement. In *Improving Water Productivity through Deficit Irrigation: Examples from Syria, the North China Plain, and Oregon USA*, 301-309. J. W. Kijne, R. Barker, and D. Molden, eds. Wallingford, U.K.: CABI Publishing.